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REP-RATE JITTER AND ELECTRODE EROSION OF A HIGH PRESSURE FLOWING OIL SWITCH (PREPRINT)

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14. ABSTRACT
A repetition rate switch has been developed at the University of Missouri for long service life applications at moderate energy levels. The switch was designed to study the effects of pressure, flow and charge voltage upon the breakdown performance of a synthetic avionics dielectric coolant known as poly-olefin. Experimental results at pressures from 3.45 to 10.34 MPa (500 to 1,500 psig) and flow rates from 0.315 to 0.694 L's-l (5 to 11 gpm) indicate the range of parameters chosen for examination does not limit the switch breakdown performance at a repetition rate of 15 pps. The electrodes were examined at 106 shots in order to estimate an electrode lifetime. The material removed, although significant, was not found to limit the performance of the switch over its test lifetime and with gap-spacing adjustments the switch was found to perform similarly to the performance observed early in the electrode lifetime. The electrodes are expected to last for more than 10^7 shots.

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REP-RATE JITTER AND ELECTRODE EROSION OF A HIGH PRESSURE FLOWING OIL SWITCH

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Abstract

A repetition rate switch has been developed at the University of Missouri for long service life applications at moderate energy levels. The switch was designed to study the effects of pressure, flow and charge voltage upon the breakdown performance of a synthetic avionics dielectric coolant known as poly-α olefin. Experimental results at pressures from 3.45 to 10.34 MPa (500 to 1,500 psig) and flow rates from 0.315 to 0.694 $L{\cdot}s^{-1}$ (5 to 11 gpm) indicate the range of parameters chosen for examination does not limit the switch breakdown performance at a repetition rate of 15 pps. The electrodes were examined at 10^6 shots in order to estimate an electrode lifetime. The material removed, although significant, was not found to limit the performance of the switch over its test lifetime and with gap-spacing adjustments the switch was found to perform similarly to the performance observed early in the electrode lifetime. The electrodes are expected to last for more than 10^7 shots.

I. INTRODUCTION

Pressurized flowing oil switches represent the newest frontier in high energy, repetition rate switch technology. Research at the University of Missouri – Columbia suggests that high-pressure oil switch technology is not merely a novel concept, but a viable one as well. The switch was found to perform with remarkable consistency over the first one million shots, and the dielectric oil was not found to degrade with time or shot count.

High-pressure oil is utilized as the switching medium in the test switch described. During a discharge in any liquid a gas bubble is generated as a by-product of the arc channel [1, 2]. The gas bubbles that remain are generally more vulnerable to breakdown than the bulk liquid, and therefore limit the maximum repetition rate the switch may be operated at. Non-steady state gas bubbles exhibit oscillatory behavior—the volume of the bubble increases and decreases with a predictable period. The size of the bubble and the period of the oscillation may be reduced by exerting greater external hydrostatic pressure, as predicted by Rayleigh and verified by Kattan *et. al.* [3, 4]. The viscous nature of oil tends to damp the oscillations over several oscillation periods [5]. The maximum repetition rate may therefore be extended by operating at higher pressure to reduce the non-steady state gas-phase oscillations [6, 7].

In addition to pure oscillations, gaseous cavities may break apart into smaller cavities during the violent collapse phase predicted by Rayleigh. This behavior has been confirmed experimentally and appears to be exacerbated by constraining geometries [7]. Utilization of high-pressure oil reduces the amount of time these microcavities are allowed to remain in suspension before being absorbed into the oil.

The discharge also generates a number of solid-phase by-products that can influence the switch breakdown performance. The solid-phase by-products include ablated electrode material and solid carbon. The carbon results from electronic dissociation and combustion of the oil dielectric during the discharge. Metal and carbon particles suspended in oil will both conduct electricity and must therefore be removed between shots. The particles are swept away from the electrically stressed region of the switch by flowing the oil in which the particles are suspended.

II. TEST STAND

The test switch is mounted at the end of a 4.8 Ω, 35 ns (one-way) water pulse forming line. The water pulse forming line (PFL) is pulse charged to –250 kV in 2.5 µs. The switch discharges the PFL into a 4.2 Ω load consisting of a series of twelve parallel 50 Ω, 70 ns (one-way) coaxial cables terminated into a 4.2 Ω low-inductance water load. The coaxial cables represent a wide-band constant impedance and temporally isolate the load from the switch. A schematic diagram of the test stand is provided in Figure 1 and is discussed in greater detail elsewhere [8].

A hydraulic pump provides independent control of pressure and flow rate, allowing any pressure and flow rate configuration within the operating limits of the pump.

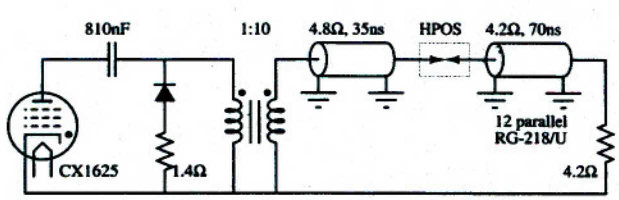

Figure 1. Schematic diagram of the thyratron-modulated high pressure oil switch (HPOS) test stand.

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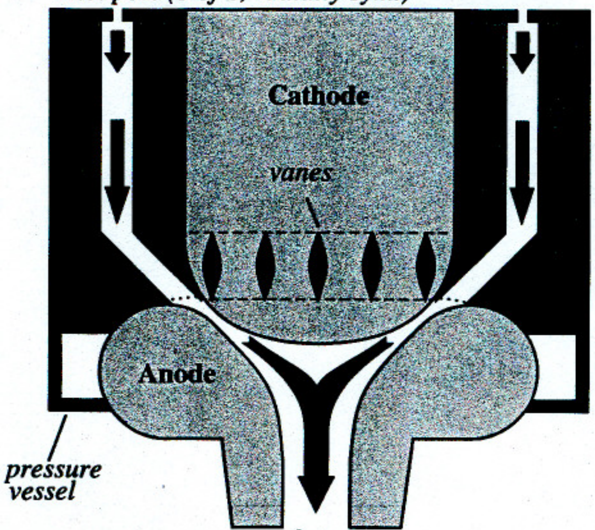

Figure 2. Cutaway diagram of the high-pressure oil test switch showing oil flow shaper details.

The pump can generate pressure in the range of 0.101 to well over 17.24 MPa (0 to 2,500 psig) and flow rates from 0 to 0.710 $L \cdot s^{-1}$ (0 to 11.26 gpm). The pressurized oil is passed through a high performance oil filter to remove particles down to 0.45 μm diameter. Pressure is developed within the high-pressure switch by throttling the downstream oil flow with a needle valve. Hydraulic resistance within the switch results in a 207 kPa (30 psig) pressure drop across the switch at 0.694 $L \cdot s^{-1}$ (11 gpm).

The test switch utilizes a pin-in-hole geometry for the electrodes, as suggested by the cutaway diagram in Figure 2. The cutaway diagram shows the anode and cathode as well as the pressure vessel and the oil flow shaping elements. The flow shaping elements were added to increase the oil flow performance, which subsequently increased the switch performance by decreasing the jitter magnitude. A photograph of the switch is provided in Figure 3. In Figure 3 the PFL connects to the top of the switch, oil flows into the port on the side, the conic-shaped part is the high-pressure polymer vessel, the plate at the bottom serves as the high-voltage output feed, and the oil flow is directed out of the tube that extends below the switch. The oil flow tube that extends from the bottom serves a dual function as the electrode adjuster.

III. Experiment

An experiment was performed to study the effects of oil pressure, oil flow rate, and maximum charge voltage on the breakdown performance of the switch. The experiment was performed following 500×10^3 shots. Analysis of variance techniques were utilized to perform the comparison.

The experiment was designed to provide information about main effects related to each of the three variables, as well as interactions between the three variables. The experimental framework employed to test the three variables was a 3×3 factorial design [9]. In the 3×3 factorial design the three variables are studied at three different levels each. All 27 of the possible combinations are tested in a randomized order. The process of testing each of the 27 combinations was repeated two additional times in which the ordering was re-randomized.

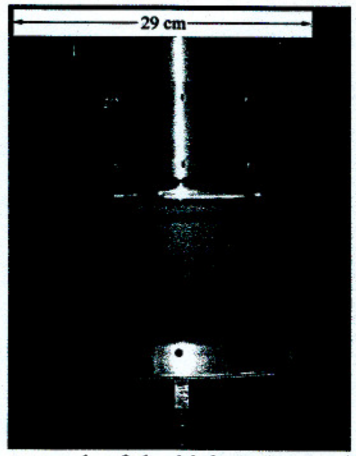

Figure 3. Photograph of the high-pressure oil switch. The PFL connects to the top, the high-voltage output is taken from the bottom plate.

The data for an entire experiment was collected over the course of a single day and all unstudied variables (*e.g.* oil temperature, repetition rate, and time between bursts) were held as constant as possible. A passively integrated, fast D-dot probe was utilized to monitor the cathode voltage charging waveform. A single burst of 100 consecutive shots at 15 pps was recorded on a digital oscilloscope (Tektronix TDS5054) for each of the 27 experimental combinations. Individual bursts were initiated every 5 minutes, and the oil temperature was maintained at 21 °C.

The data were analyzed by extracting the time to breakdown, defined as the difference between the time at breakdown and the time at a specified threshold value. Time to breakdown was utilized, rather than the voltage at breakdown, because the peak charging voltage was varied between three levels and was therefore not directly comparable. Time to breakdown was easily extracted and provided more accurate comparisons.

The data were finally compared utilizing standard analysis of variance techniques. Analysis of variance, or ANOVA, provides a useful indication of the degree to which a variable, or interaction of variables, is related to trends in the data. The ANOVA statistical analysis was performed on the 100-shot mean value for each of the 27 combinations, and each of the 3 experimental replications. Jitter was also analyzed with ANOVA.

The jitter was quantified by the inter-quartile range of the time to breakdown. The inter-quartile range, or IQR, is defined as the middle 50% of the observations—i.e. 25% of the data above the median and 25% of the data below the median. The IQR was utilized here because it tends to define the range where most of the data in a non-Gaussian distribution may be found. The standard deviation, which is typically used to describe the statistical variation, more properly describes how tightly

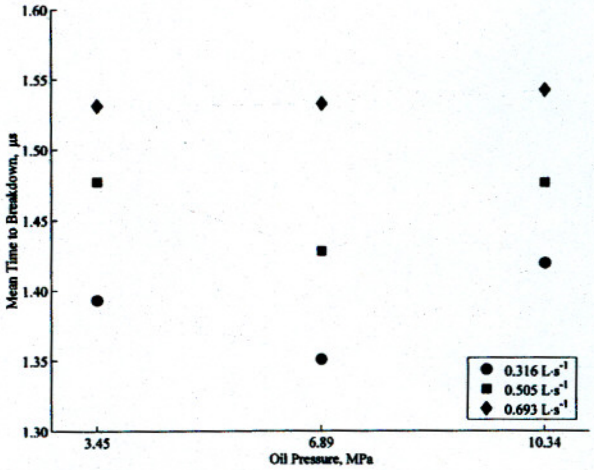

Figure 4. The 100-shot mean time to breakdown as a function of pressure and flow.

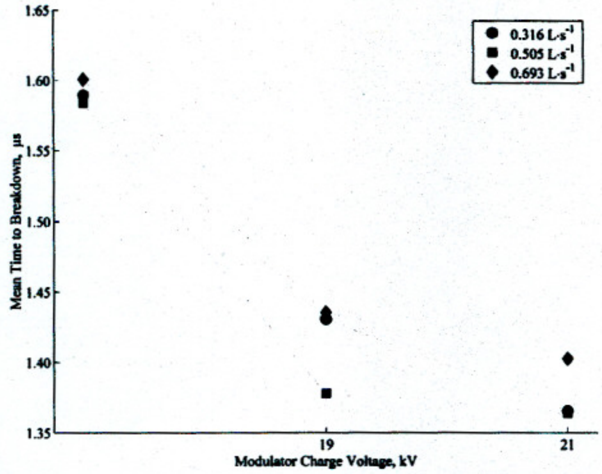

Figure 5. The 100-shot mean time to breakdown as a function of voltage and flow.

the data bunches up around the mean.

IV. Results

The results presented are from data taken at 500×10^3 shots, immediately following an electrode gap adjustment. The oil pressures examined were 3.45, 6.89, and 10.34 MPa, which correspond to 500, 1000, and 1500 psig, respectively. The oil flow rates examined were 0.316, 0.505, and 0.694 $L{\cdot}s^{-1}$, which correspond to 5, 8, and 11 gpm, respectively. The voltage levels were 17, 19, and 21 kV.

Data was additionally taken every 10,000 shots in the build-up to 1×10^6 shots to study the effect of electrode age on breakdown performance. At 10,000 shot intervals an entire series of 1,000 shots was recorded. All of the data presented in the lifetime study was collected utilizing 15 pps bursts and performed at 6.89 MPa and 0.442 $L{\cdot}s^{-1}$ (7 gpm).

A. Factorial Experiment

Figure 4 depicts an interaction plot of oil pressure and oil flow rate for the mean time to breakdown. The mean time to breakdown is observed to increase in a linear fashion as the flow rate is increased linearly, as suggested by the even spacing between the groups of data. The difference in mean time to breakdown between the highest and lowest pressures, at each flow rate, indicates the breakdowns take place at higher relative voltages as the pressure increases. There appears to be a non-linear interaction between the pressure and flow rate, and the interaction may be damped out by higher flow rates.

Figure 5 depicts an interaction plot of peak charging voltage and oil flow rate for the mean time to breakdown. It is evident from the shape of the curves that charge voltage plays the most significant role in defining the time to breakdown. The negative slope of the curves is intuitively obvious and results from increasingly extreme gap over-voltage.

Figure 6 depicts an interaction plot of peak charge voltage and oil pressure for the mean time to breakdown. Again it is clear that charge voltage plays a major role in the mean time to breakdown. There is additionally a clear

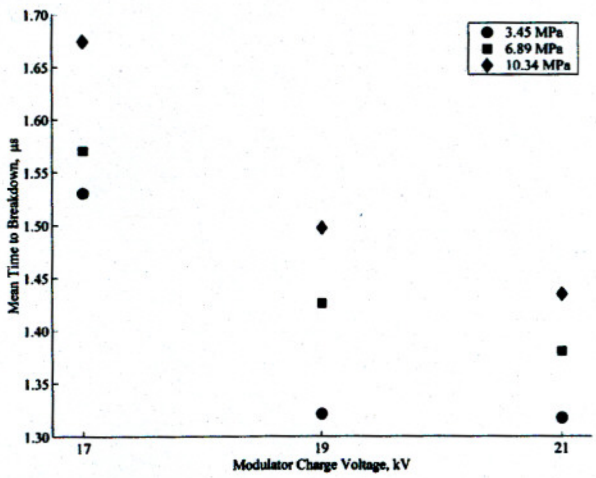

Figure 6. The 100-shot mean time to breakdown as a function of voltage and pressure.

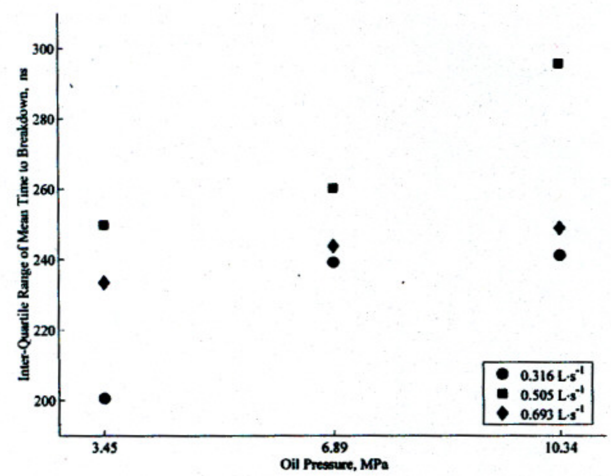

Figure 7. The 100-shot inter-quartile range of time to breakdown under varying oil pressures and flow rates.

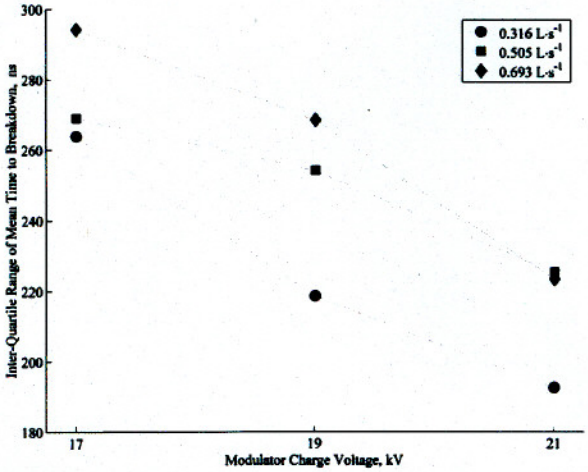

Figure 8. The 100-shot inter-quartile range of time to breakdown under varying charge voltages and flow rates.

pressure dependence, lower pressures resulting in lower breakdown voltages, or equivalently, earlier breakdown.

The pressure dependence observed in Figure 6 was not completely unexpected because the electrode gap spacing is linearly dependent upon oil pressure—as the oil pressure increases the gap spacing increases. The pressure dependence observed appears to be linear, which is suggested by the spacing between different levels of pressure. The magnitude of the spacing is roughly consistent with the anticipated increase in time to breakdown due to the pressure-dependent gap spacing.

The effects of the interaction between oil pressure and oil flow rate upon the range of the middle 50% of the data is presented in Figure 7. In all three cases the range of the middle 50% of the observations, the inter-quartile range (IQR), at the lowest pressure is clearly less than the IQR at the highest pressure and therefore suggests a linear dependence of IQR on oil pressure. The two extreme oil flow rates produced the lowest IQR's.

The interaction plot of the IQR as a function of charge voltage and oil flow rate is presented in Figure 8. The data suggests both a linear and a non-linear component of interaction between charge voltage and oil flow rate. Increasing the charge voltage linearly results in a linear decrease in the IQR, which suggests the distribution of

Table I. Significance of source terms in driving the experimental variation. †Strongest relationship detected.

Source	Mean, %	IQR, %
P	100.0	99.98
F	80.7	99.6
V	100.0†	100.0†
PF	4.65	77.7
PV	28.2	64.3
FV	2.53	36.4
PFV	71.3	49.2
R	97.3	75.2

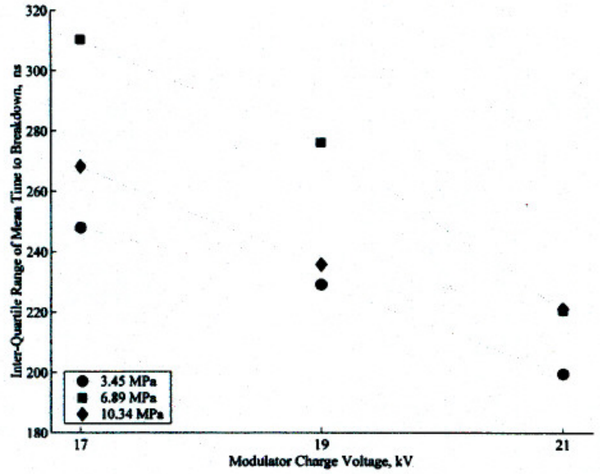

Figure 9. The 100-shot inter-quartile range of time to breakdown under varying charge voltages and oil pressures.

shots about the mean has tightened up for higher charge voltages. It is also clear from Figure 8 that the IQR tends to be larger when the oil flow rate is greater.

The interaction plot presented in Figure 9 shows the relationship between the IQR, the oil pressure, and the charge voltage. As was observed in Figure 4 with the voltage-flow interaction, there is a clear linear dependence of the IQR upon the modulator charge voltage, with the IQR decreasing for increasing charge voltage. A non-linear dependence of the IQR on the oil pressure is evident in Figure 9, as the IQR appears to maximize when the oil pressure is at 6.89 MPa. The lowest oil pressure resulted in the lowest IQR.

The numerical results presented in Table I agree with the graphical analyses presented in Figures 4 through 9. The ANOVA procedure assigned to each source term a probability that gives the likelihood of the particular source term resulting in an observed variation. The probabilities are summarized in Table I. The source terms are oil pressure (P), oil flow rate (F), switch charge voltage (V), interactions involving pressure, flow, and voltage (PF, PV, FV, PFV), and experimental run (R).

The analysis of the mean time to breakdown revealed charge voltage and oil pressure as the two greatest factors driving the observed experimental variation. The results of the analysis with respect to the charge voltage relationship are not surprising given the evidence already presented in Figures 5 and 6. The mean time to breakdown was also affected by the pressure, which is also not a surprise due to the relationship between gap spacing and oil pressure. The strong dependence upon the experimental run is probably due to the effects of electrode ablation—the fact that the ANOVA procedure found this effect means that its effects could be differentiated from, and therefore removed from the observed response. No other terms, specifically the interactions, had any significant effect upon the breakdown.

The jitter analysis presented under the IQR column in

Table I suggests that all three of the variables studied played a significant role in driving the IQR. The numbers presented in Table I, taken in conjunction with Figures 5, 6, and 7 suggest the relationships involved are not necessarily linear. The pressure-voltage and pressure-flow interaction plots for the IQR indicate definite maximum values. Neither the interaction terms involving pressure, flow and voltage, nor the switch lifetime manifest as the experimental run appear to have played any significant role in driving the observed inter-quartile ranges.

B. Lifetime Study

The mean time to breakdown was also observed over the course of the experiment. The mean time to breakdown for shots 580×10^3 to 1×10^6 is presented in Figure 10. The plotted data points resulted from an analysis of 1,000 consecutive shots taken every 10,000 shots over the range presented. The data was taken with a modulator charge voltage of 22 kV, an oil flow rate of 0.442 $L \cdot s^{-1}$, an oil pressure of 6.89 MPa, an oil temperature of 21 °C, and at a repetition rate of 15 pps. The graph shows the mean time to breakdown increasing linearly with the shot count. The IQR of the data appears to remain constant over the range of shots presented.

The remarkable aspect of Figure 10 is that the statistical processes governing breakdown do not appear to be strongly influenced by the electrode wear. Moreover, as the gap spacing gradually opened up the IQR of the distribution remained generally unchanged. The earliest mean breakdown data point in Figure 10 corresponds to breakdown at 58% of the peak voltage level while the last mean data point plotted corresponds to breakdown at 70% of the peak voltage level. Under the modulation scheme both of these levels lie within the linear region of the '1-cos(ωt)' curve and the dv/dt is in the range of 100 – 200 kV/µs.

V. Conclusions

The results from both an experiment and a study were presented. The results from the experiment suggest that

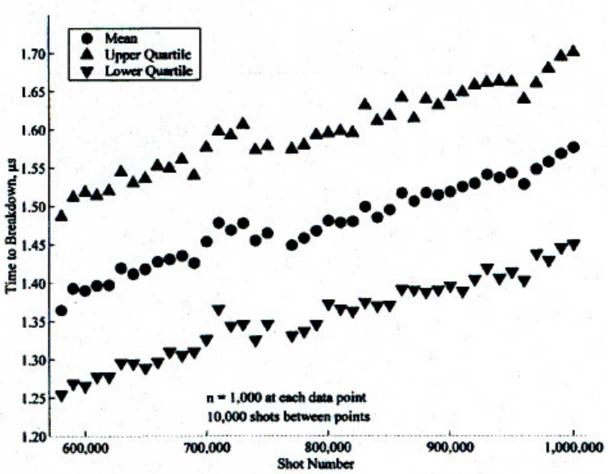

Figure 10. Progression of the average time to breakdown and IQR over part of the electrode lifetime.

the mean breakdown voltage may be controlled by adjusting the peak charge voltage and the oil pressure. Increasing the peak charge voltage reduces the mean time to breakdown while increasing the oil pressure increases the mean time to breakdown. The data plotted in Figure 4 also suggest that a decrease in the flow rate can reduce the mean time to breakdown.

Examination of the inter-quartile range provided information about the shape of the distribution of shots. The data suggests that operating at higher charge voltages reduces the width of the distribution at the 25^{th} percentiles. The data may also indicate a saturation effect as a function of either oil pressure or flow rate in Figures 7 and 9. The exact cause of this is unknown and additional investigation is planned.

A simple study on the effect of electrode age on the time to breakdown was performed to investigate claims on electrode lifetime. The study indicates that for mean time to breakdown that remains roughly within the linear dv/dt range of the charging waveform the mean time to breakdown increases linearly with the electrode age and the IQR remains constant. It appears that the electrodes will perform consistently from gap adjustment to gap adjustment. This claim will be verified experimentally.

VI. Acknowledgements

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